CCD Requirements for Digital Photography

Richard L. Baer
Hewlett-Packard Laboratories, Palo Alto, California

Abstract

Digital photography has the potential to supersede conventional film photography. In order to realize this potential, digital photography needs to provide the best image quality and highest utility. We have used our modeling of photographic systems and our experimental measurements of CCDs in order to estimate the photographic potential of specific CCDs. We have also extrapolated the future requirements for CCDs that can compete with film.

In order to make meaningful sensitivity comparisons, we have developed a model that can be used to predict the ISO speed potential of a digital camera, based on the characteristics of the CCD. The model is briefly described in the second section of the paper. The model can also be used to qualitatively analyze the effect of CCD parameters on camera performance, and examples of the effects that limited charge capacity have on image quality and read noise have on ISO speed are presented. A simple relationship for the ISO speed in the monochrome case is also presented in order to illustrate the scaling laws.

We have tested a large number of CCDs of varying architecture in order to collect input data for our speed model. We have designed a universal CCD evaluation camera in order to test these CCDs under similar conditions, with minimum hardware modifications. We have used the camera and an optical monochrometer system to measure parameters including the full-well capacity, linearity, quantum efficiency, dark current, read noise, smear and angular response of many of the CCDs that represent the current state of the art. The camera and the methods that we have used to perform these tests are described in the second section of this paper.

The effect that different CCD characteristics have on image quality and camera utility are described in the third section of this paper. For comparison, we present the measured characteristics that represent the current state-of-the-art for commercially available CCDs. We also postulate the performance required for CCDs to compete with film

The paper concludes with our comments on the most appropriate CCD architectures for digital photography, and suggestions for future CCD development.

ISO Speed Model

We developed our photographic speed model in order to make meaningful comparisons between the sensitivities of different CCDs, and between CCDs and film. The model accepts as its inputs the measured characteristics of a CCD and produces as its output an estimate of the photographic speed. The speed has the same interpretation as the ISO speed for photographic film, in that it specifies the correct nominal exposure conditions (f-stop, exposure period) for a given scene brightness.

The ISO speed model is based upon International Standard ISO 12232, Photography – Electronic still-picture cameras – Determination of ISO speed[1]. The standard describes a procedure for determining the noise-based speed range of a digital camera, based on the focal-plane illumination required to achieve a specific mid-tone signal-to-noise ratio.

Our calculation is conducted in three steps: evaluation of the CCD responsivity, determination of the signal to noise (S/N) ratio as a function of focal plane exposure, and determination of the ISO speed from the S/N ratio. A description of the model can be found in reference 2.

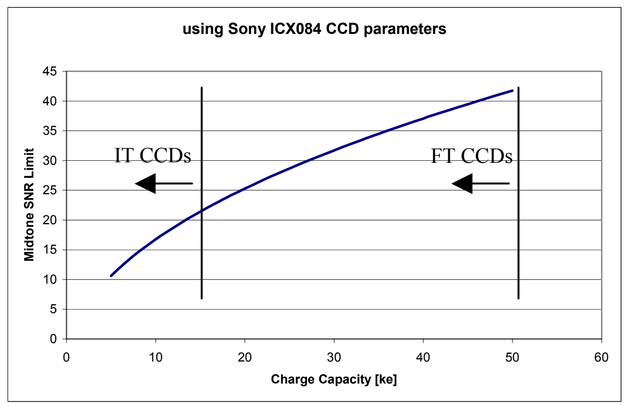

Figure 1 – Mid-tone SNR vs. Charge Capacity

In addition to using the model to predict camera speeds, we have used it to qualitatively determine the influence of various CCD parameters. The maximum mid-tone signal to noise ratio is plotted as a function of the linear charge capacity in figure 1, using CCD parameters from the Sony ICX084. The mid-tone SNR is a measure of image noisiness. A value of 10 is considered acceptable, and a value of 40 is considered excellent. As the figure shows, high mid-tone SNRs are not accessible with IT CCDs because of their limited charge capacity.

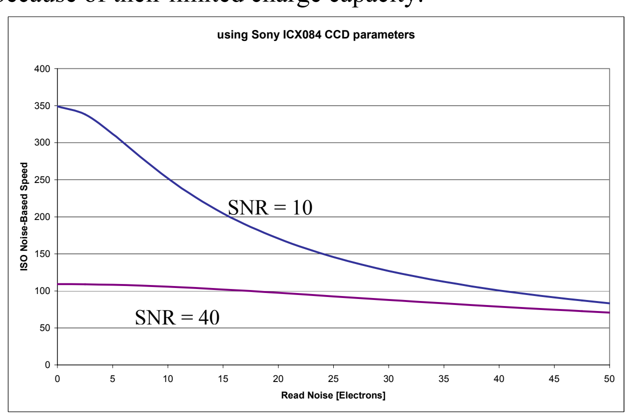

Figure 2 –ISO Speed vs. Read Noise

The ISO noise-based speed is plotted as a function of the read noise level in figure 2. The lower curve corresponds to SNR 40 (excellent quality), and the upper curve corresponds to SNR 10 (acceptable quality). The dominant source of noise in the excellent quality case is the shot noise of the photon flux. Read noise has a much stronger influence in the acceptable quality case, which corresponds to the highest speed at which the camera can be operated.

An analytical expression for the speed can be derived in the monochrome case, where only the luminance channel is present. The monochrome speed appears in Equation 1. In this equation A is the pixel area, η_p is the photopic quantum efficiency (proportional to the CCD quantum efficiency), N_r is the read noise level (in electrons) and S/N_x is the mid-tone signal to noise ratio upon which the speed is based.

$$S_{noisex} = \frac{20 A \eta_p}{S/N_x^{\ 2}} \left(1 + \sqrt{1 + \frac{4N_r^2}{S/N_x^{\ 2}}} \right)^{-1} \qquad (1)$$

The key CCD parameters that effect the ISO speed are the pixel area, the quantum efficiency and the read noise.

CCD Evaluation

Measurement System:

We have developed a universal CCD test camera that can be used to evaluate a wide range of CCDs with minimal hardware modifications. We have used the camera to test CCDs from five different manufacturers, including full-frame, frame transfer, and interline transfer devices using both progressive and interlaced scan. The camera is flexible enough to conduct complicated measurements such as separating the VCCD and photodiode dark current contributions in interline transfer CCDs.

The design of the breadboard camera is modular. The modules plug into a custom backplane that routes power and digital signals. The backplane provides both bus and direct module-to-module interconnections. The major modules are an imager board, a timing generator, an analog processor and a frame grabber interface. We have also developed power supply and shutter control modules, in addition to special purpose modules like an arbitrary waveform generator interface.

The imager board contains all the imager-specific electronics, including horizontal and vertical CCD drivers and bias voltage generation. It also includes an analog buffer amplifier for the output of the CCD.

The timing generator consists of a clock oscillator and two programmable logic devices. One device generates all the pixel-level timing (e.g. reset gate, serial clock, A/D sample pulses) and the other device generates the line and frame timing (e.g. vertical clocks, sync pulses). The PLDs can be reprogrammed to support virtually any CCD and any clocking scheme. The PLDs are controlled by a serial data loop that runs through all the modules of the camera, and is driven by the host computer.

The analog processor utilizes two 12-bit A/D converters to separately sample the preset and video levels. The digital outputs pass through a programmable logic device which implements digital CDS.

The frame grabber interface adapts the camera to a number of different frame grabbers, including the Imaging Technology AM-DIG and the Data Translation DT3157.

The software that controls the camera is written in Visual C++ and runs on Windows/NT and Windows/95 computers. A configuration file is used to adapt the camera program to a particular CCD. It has sophisticated image analysis capabilities, such as a temporal variance calculation, that simplify CCD characterization. It provides many different views of the image data and can save the data in many different file formats. A DLL version of the program has also been written which can be called from HP VEE or LabView in order to automate test procedures.

The test camera is used with an optical system that consists of a tungsten halogen source, a set of optical filters, an Oriel MS257 monochrometer, and an integrating sphere. The optical filters are used to prevent light at the higher harmonic frequencies of the grating from reaching the integrating sphere. A diode optical power meter is attached to a monitoring port on the integrating sphere in order to determine the incident power level. A second optical power meter is used to calibrate the system.

Basic CCD performance tests:

Our basic test suite consists of seven measurements:

a) Photon transfer curve – The photon transfer curve plots the temporal variance as a function of the mean output level of the camera[3]. In this experiment the CCD is illuminated uniformly with the integrating sphere. The values of all the pixels in the central 64 by 64 pixel block are averaged together to increase the accuracy of the measurement. The temporal variance is calculated by differencing two successive frames. The overall system gain (in DN/e) can be determined from the slope of the curve. The system gain and the saturation level can be used to calculated the full-well capacity. The conversion gain (in uV/e) can be calculated from the system gain if the electronic gain of the camera is known. The read noise can be determined from the temporal variance in the absence of illumination.

b) QE vs. wavelength – The quantum efficiency versus wavelength curve is obtained by measuring the response of the CCD to narrow band illumination from the monochrometer. The power meter on the monitoring port of the integrating sphere measures the illumination level. The system gain that was calculated in the photon transfer curve measurement is used to relate the CCD output signal to the absolute charge level.

c) Collimated QE at one wavelength – CCDs that incorporate micro-lenses accept only a limited angular spectrum of light. If the f-number of the test system is lower that the f-number of the micro-lens, some of the incident light will be lost, and the measured quantum efficiency will be erroneously low. The effective f-number of the integrating sphere, from the perspective of the CCD, is only about f/1.1. In order to correct for this effect, we make a QE measurement with collimated light at a single wavelength by removing the integrating sphere from the system. The illumination level is determined by substituting an optical power meter for the CCD, using a laser beam to make sure that the two detectors are placed in exactly the same position. The QE measured at this wavelength is used to correct the remainder of the QE curve. The correction can be as large as a factor of six.

d) Angular response – In order to measure angular response, the integrating sphere is removed from the test system, and the CCD is placed in the collimated beam emerging from the monochrometer. The response of the CCD is measured as a function of its rotation angle. The rotation angle is determined by observing the position of the reflection from the CCD and its cover glass on the case of the monochrometer. Our apparatus is currently limited to incident rays within 22.5 degrees of normal, although the method could be extended to much higher values.

e) Dark current – We measure dark current by collecting a single frame with a long exposure period (typically 4 seconds), and analyzing the statistical distribution of the pixels. In the case of interline transfer CCDs, this gives us the distribution of the photodiode dark current. In the case of frame transfer CCDs, this gives us the distribution of VCCD dark current. We use special timing to measure the VCCD dark current in IT CCDs. The special timing freezes the vertical register during the exposure period and eliminates the photodiode to VCCD transfer.

f) Smear – We measure smear in interline transfer CCDs by using a special timing program that inhibits the photodiode to VCCD transfer. In this mode, the effective integration time is one frame period. This response is compared to the response of the CCD at a lower level of uniform illumination, with the photodiode transfer enabled. We then report these values in terms of the standard 1/10th frame height white block smear test.

g) PRNU – We average many frames together at a moderate level of exposure in order to characterize the PRNU. Averaging is required to reduce the influence of photon shot noise. The image is then normalized by a blurred copy of itself in order to eliminate shading variations. The resulting distribution is analyzed.

CCD Requirements and the Current State of the Art

The quality of a digital image is dependent on many of the performance characteristics of the CCD. The most important characteristics are included in the following list, along with a description of what impact that parameter has on the utility of the camera or the quality of the image. Measured values that represent the current state of the art are presented.

a) High quantum efficiency – The quantum efficiency is one of the prime determinants of sensitivity. State of the art IT CCDs with RGB filters have peak quantum efficiencies of greater than 40% in the green while FT CCDs have peak quantum efficiencies of 20%. Assuming a 5 um pixel size, the associated ISO speed range for the IT CCD would be about 60 to 320, which is comparable to the performance of film In order to exceed the capabilities of film with smaller pixels, peak quantum efficiencies of greater than 50% will be required.

b) Large charge capacity – The signal to noise ratio increases as the square root of the number of electrons captured. The larger the charge capacity, the higher the potential signal to noise ratio in the image. The dynamic range and the exposure latitude also depend on the charge capacity. State of the art interline transfer CCDs (designed for digital cameras) have linear charge capacities of up to 15,000 electrons, while the best frame transfer CCDs have linear charge capacities of more than 50,000 electrons (assuming ~5 um pixel). As figure 1 shows, charge capacities of at least 30,000 electrons will be required to reach the highest levels of image quality.

c) Low read noise – As figure 2 shows, the read noise has a strong influence on the ultimate sensitivity of the camera under poor lighting conditions. The overall noise floor of a camera depends on the CCD conversion gain as well as the read noise. The best IT CCDs have conversion gains of up to 38 uV/e, and read noise levels as low as 12 electrons (in a 20 MHz bandwidth), while the best FT CCDs have conversion gains of up to 23 uV/e, and read noise levels as low as 15 electrons. The sensitivity improvement that could be obtained by eliminating read noise is less than a factor of 1.5 over the current state of the art, so this may not be the best candidate for further improvement. Any read noise improvement will require a commensurate conversion gain increase, since most analog signal processing circuits have equivalent input noise levels of about 50 uV, and most digital cameras have even higher levels of internal interference.

d) Low dark current – The dark current effects the maximum practical exposure time and the usability of the camera at high temperatures. Excessive dark current accumulation during readout can also contribute to the read noise.

The dark current pattern of a state of the art CCD looks like a picture of the night sky on a moonless night. The vast majority of the pixels have negligible responses and the others look like isolated stars of varying magnitude. The best IT CCDs that we have measured have average photodiode dark current densities of ~3pA/cm^2 at room temperature. The best FT CCDs have VCCD dark current densities of ~15 pA/cm^2. The state of the art dark current levels of the photodiodes of IT CCDs and the VCCDs of FT CCDs are low enough to allow multi-second exposures at room temperature. This compares favorably with film, which suffers from reciprocity failure at long exposure periods.

The VCCD dark currents of modern IT CCDs are very high in comparison. We typically measure VCCD dark currents in IT CCDs of ~1 **nA**/cm^2. The lowest VCCD dark current density we have measured in an IT CCD is ~ 700 pA/cm^2.The shot noise of the dark current accumulated during readout in a typical IT CCD is about 10 electrons, which is comparable to the read noise. Efforts should be made to reduce the dark current density to ~ 100 pA/cm^2 so as to enable IT CCDs to maintain low read noise at high temperature.

e) Selective, smooth color filters – Selective color filters are required to obtain high color accuracy. We have determined that selective primary color filters provide better color quality that broad complementary color filters[4]. Smooth filters are preferable because their response isn't effected much by slight spectral differences in narrow band sources, such as fluorescent lights. State of the art IT CCDs have excellent filter responses. The responses of FT CCDs exhibit ripples because of interference effects in the gate electrodes and oxide layers. The manufacturers of FT CCDs should aspire to match the IT CCD spectral characteristics.

f) Good linearity – Look up tables can only be used to correct nonlinearities if the nonlinearities are stable and uniform across the array. Inaccuracies in the correction will have an especially severe effect on color quality, since the color value is derived from the ratios of the levels of adjacent pixels. State of the art CCDs have excellent linearity. IT CCDs often have an extended nonlinear range of response above the linear range, which is not useful in digital photography.

g) Low smear – Most modern digital cameras use a mechanical shutter to eliminate smear during still image capture. However smear is still an important problem in preview, auto-focus and auto-exposure modes, which depend on electronic shuttering. If the smear level is high, the camera could auto-focus on features in the wrong part of the image. State of the art IT CCDs designed for consumer digital photography have smear levels as low as –70 dB. The smear level of an FT CCD is limited by the speed of the vertical driver, and is typically about –60 dB. Smear levels of –70 dB are adequate for digital cameras that utilize the CCD for focus and exposure control. Smear would be unimportant in a camera that used ancillary sensors to accomplish these functions.

h) Broad angular response – A camera's ability to collect images at low light levels is determined by the aperture stop (f/#) of the lens as well as the sensitivity of the imager. As the f/# is decreased, the exposure increases, but so does the breadth of the angular spectrum of rays incident upon the CCD. If the angular response of the CCD is too narrow, the oblique rays will be lost, and the sensitivity increase that would be expected from a decreased f/# will not be obtained.

State of the art interline transfer CCDs have much narrower angular responses in the horizontal direction than in the vertical direction. Typical IT CCDs that we have measured have +/- 9 degree horizontal and +/- 17 degree vertical responses (50% response point). The best IT CCDs have +/- 12 degree horizontal and +/- 23 degree vertical responses. The frame transfer CCDs we have tested do not use microlenses, and have angular responses of > 25 degrees along both axes.

i) Low PRNU – Random pixel response variations become the dominant source of noise at high signal levels. Shading variations across the CCD are less important. State of the art CCDs typically have random PRNU values of < 2.5%. Assuming a charge capacity of 30,000 electrons, The random variation at the mid-gray level due to the shot noise of the photon flux is about +/- 1.5%. In order to obtain the highest image quality, the random PRNU of the CCD should be kept below the shot noise level.

j) Strong anti-blooming – Many scenes contain specular highlights. The highlights do not have to be reproduced accurately, but they must not bloom and disrupt other portions of the image. The 100X anti-blooming that is typical of the state of the art is adequate for digital photography.

k) Limited defects – In digital photography, many defects can be corrected by interpolation. However some defects, such as column defects and large cluster defects can not be easily corrected and should be avoided. State of the art CCDs have many isolated defects, and few cluster defects, and are adequate for digital photography.

Conclusions

This work has been necessitated by the fact that the specification sheets published by many CCD manufacturers are inadequate. Every manufacturer should provide quantum efficiency versus wavelength, linear charge capacity, conversion gain, read noise, photodiode and VCCD dark current densities, smear level and angular response data for their CCDs.

From the perspective of the camera manufacturer, improvements in several areas of CCD performance would be desirable. Increases in quantum efficiency and decreases in read noise (and VCCD dark current, in the case of IT CCDs) would lead directly to increases in photographic speed. Improvements in the angular response of IT CCDs would enable the use of faster lenses. Improvements in the charge capacity of IT CCDs would provide more dynamic range and higher image quality.

Camera sensitivity is linearly proportional pixel area. The only way to improve the photographic quality of a digital camera in terms of both resolution and sensitivity is to increase the sensor area. A good metric for the utility of an image sensor in digital photography is the product of resolution and ISO speed, which is proportional to the product of the sensor area and the peak quantum efficiency. Larger sensors and higher quantum efficiencies will enable digital cameras to displace film cameras.

References

1) ISO 12232: Photography – *Electric still-picture cameras – Determination of ISO speed*, (1998)

2) R.L. Baer and J. Holm, "A Model for Calculating the Potential ISO Speeds of Digital Still Cameras based upon CCD Characteristics", *Proceedings IS&T PICS Conference*, (in press), Savannah, Georgia, (1999)

3) J. Janesick, K. Klaasen, T. Elliott, "CCD Charge Collection Efficiency and the Photon Transfer Technique", *Optical Engineering*, Vol. 8, (1987)

4) R.L. Baer, W.D. Holland, J. Holm, P. Vora, "A comparison of Primary and Complementary Color Filters for CCD-based Digital Photography", *Proceedings IS&T/ SPIE Symposium on Electronic Imaging*, San Jose, CA, pp. 16-25, 1999.